

Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production

Test Plan for Reactor Graphite Elements

Prepared by General Atomics for the Battelle Energy Alliance, LLC

Subcontract No. 00075309 Uniform Filing Code UFC:8201.3.1.2

GA Project 30302

















GA 1485 (REV	GA 1485 (REV. 08/06E) ISSUE/RELEASE SUMMARY												
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ACRONYMS AND ABBREVIATIONS

ASTM American Society of Testing and Materials

DDN Design Data Need

DOE U.S. Department of Energy

FSV Fort Saint Vrain
GA General Atomics

GT-MHR Gas Turbine Modular Helium Reactor HTGR High-Temperature, Gas-Cooled Reactor

HTTR High Engineering Test Reactor
INL Idaho National Laboratory
JAEA Japan Atomic Energy Agency
MHR Modular Helium Reactor

MHTGR Modular HTGR

NDE Non-Destructive Examination
NP-MHTGR New Production Modular HTGR
ORNL Oak Ridge National Laboratory

RT Room Temperature

TRL Technology Readiness Level
VHTR Very High Temperature Reactor

1 INTRODUCTION

The graphite components of the reactor are the permanent side reflector, the core support structure and the core. The core includes the fuel elements and the replaceable reflector elements. For the General Atomics (GA) commercial Gas Turbine Modular Helium Reactor (GT-MHR) the reference material for the core, permanent side reflectors, and the core support was H-451 graphite, which is no longer commercially available. The reference material for the permanent side reflector support blocks at the hot duct entrance and selected core support post blocks is a purified form of HLM grade graphite. Figure 1-1 shows the GT-MHR core assembly and support structure. Figure 1-2 shows horizontal cross section of the core assembly at midplane and Figure 1-3 shows a vertical cross section of the core assembly and support structure. Figure 1-4 shows a standard GT-MHR fuel element. A complete description of the GT-MHR core assembly and support structure graphite components is given in [Phelps 2008]. The final design of the core assembly and support structure for a block-type Next Generation Nuclear Plant (NGNP) is expected to be similar to that of the GT-MHR.

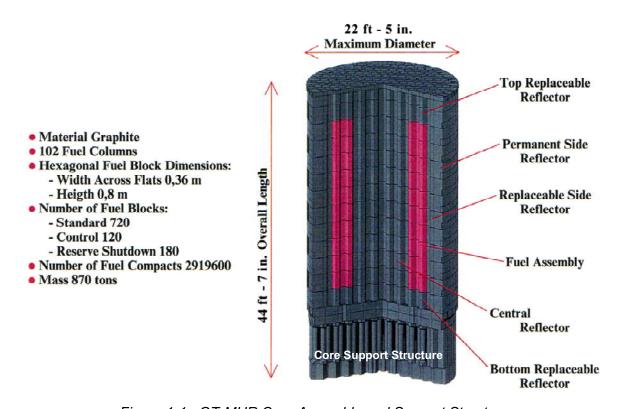


Figure 1-1. GT-MHR Core Assembly and Support Structure

¹ A listing of applicable documents for this Test Plan is provided in Section 2.

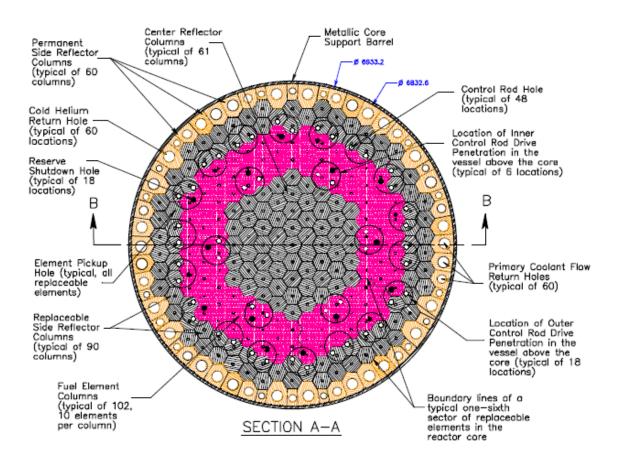


Figure 1-2. Horizontal Cross Section through the Reactor Core and Mid-Plane

Both graphite grades of selected billet sizes were used successfully in the Ft. St. Vrain (FSV) reactor, and much is known about these materials. However, the NGNP design conditions are different from those in previous reactors such as FSV and other large HTGRs. Specifically for the NGNP, designing for conduction cooldown events requires graphite properties at higher temperatures, and the currently proposed structural design criteria require new material properties to be measured, and test data used to validate the design.

Due to changes in the graphite manufacturing industry, graphite made by different suppliers and from new sources of raw materials must be characterized by testing before they can be qualified for use in the NGNP. Consequently, a high-priority for the NGNP is to identify and qualify a near isotropic graphite to replace grade H-451.

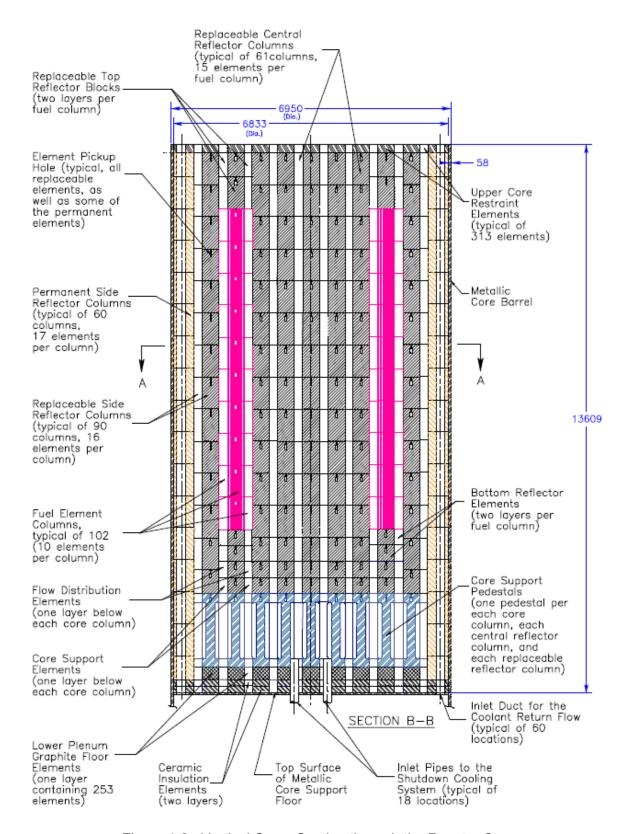


Figure 1-3. Vertical Cross Section through the Reactor Core

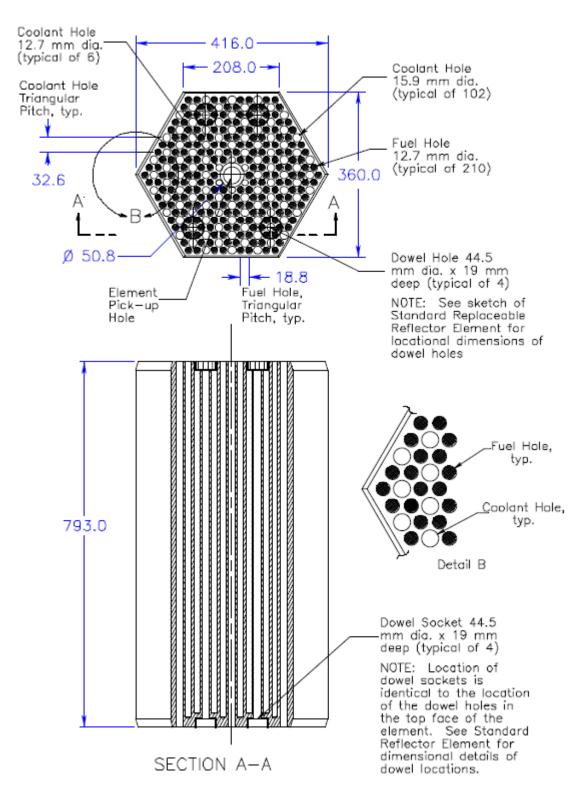


Figure 1-4. Standard GT-MHR Fuel Element

1.1 Scope

The scope of this Test Plan includes the fuel element graphite blocks, replaceable inner and outer reflector elements, upper reflector elements, and lower reflector elements (including flow distribution elements). All of these elements are hexagonal-shaped blocks manufactured from the same nuclear-grade graphite. The scope of this test plan is limited to testing performed on graphite specimens to obtain property data. Testing performed on full-size (or scaled) elements and assemblies of elements is within the scope of the Test Plan for the Reactor Core Assembly.

The permanent side reflector and core support structure graphite components are part of the Reactor Internals, but are not within the scope of this Test Plan. These components are subjected to less severe conditions of temperature and neutron fluence and generally have different design requirements than graphite elements that comprise the core and replaceable reflectors.

1.2 Purpose

The purpose of this Test Plan is to define the test programs that will raise the Technology Readiness Level (TRL) level for Reactor Graphite Elements from 6 to 7.

Nuclear-grade graphite is a mature technology and has been used previously in several HTGRS, including Ft. St. Vrain, which used block graphite elements manufactured from H-451 graphite. However, H-451 graphite is no longer commercially available and a graphite to replace H-451 is needed for a block-type NGNP core. The 30 MWt High Temperature Engineering and Test Reactor (HTTR) reactor operated by Japan Atomic Energy Agency (JAEA) in Oarai, Japan uses block graphite fuel and reflector elements manufactured from IG-110 graphite [JAEA 2006]. For NGNP, new nuclear-grade graphites are being developed and qualified, including grades PCEA, NBG-17, and NBG-18 that can be used for a block-type core.

Qualifying a new grade of nuclear graphite requires an extensive technology program and the development of an engineering design data base for both unirradiated and irradiated graphite properties. However, because of the extensive experience base with the manufacture and irradiation of nuclear-grade graphite, a clear definition of the required Design Data Needs (DDNs) and associated technology program, and the availability of IG-110 graphite for initial NGNP cores, a TRL level of 6 is judged to be appropriate for this component.

A TRL of 7 is achieved after the requisite design data have been obtained for the new graphite. These data are specified in the following Design Data Needs (DDNs):²

² The protocol for assigning DDN numbers is described in the NGNP Umbrella Technology Plan [Hanson 2007].

- C.11.03.11, Graphite Multiaxial Strength Data
- C.11.03.12, Graphite Fatigue Data
- C.11.03.13, Graphite Mechanical Properties Data
- C.11.03.14, Graphite Irradiation Induced Dimensional Change Data
- C.11.03.15, Graphite Irradiation Induced Creep Data
- C.11.03.16, Graphite Thermal Properties Data
- C.11.03.17, Graphite Fracture Mechanics Data
- C.11.03.18, Graphite Corrosion Data
- C.11.03.19, Graphite Corrosion Data for Methods Validation
- C.11.03.20, Graphite Destructive and Nondestrucive Examination Data
- C.11.03.21, Graphite Coke Source Qualification
- C.11.03.23, Graphite Oxidation Data for Postulated Accidents

JAEA Comments on Advancement to TRL-7

Based on their experience with the HTTR and IG-110 graphite, JAEA provided the following comments with regard to advancement to TRL-7:

- 1. It is important that the requirements for graphite purification and for the maximum bulk size of the graphite components be considered as early as possible during the process of material selection.
- 2. ASME design criteria are currently under development for nuclear-grade graphite. These design criteria must be completed prior to validating the graphite component design. The ASME design criteria should include acceptance criteria for allowable defects in graphite components. Non-destructive test methods (e.g., eddy current and ultrasonic testing) should be developed to measure defects with respect to the acceptance criteria.

To achieve a TRL of 8, instrumented tests are performed as part of NGNP startup testing to confirm physical, mechanical, thermal, and chemical properties. Inspections of selected fuel and reflector elements at the end of startup testing are also performed.

1.3 Background

The design of graphite components is based on a considerable body of available graphite data. In the early 1970s, a near-isotropic, petroleum coke-based graphite, designated Grade H-451 and manufactured Great Lakes Carbon (now part of SGL Carbon), was developed for use in the HTGR. Numerous test programs and experiments were conducted, mostly by GA and Oak Ridge National Laboratory (ORNL), to characterize its behavior for commercial HTGRs. Consequently, a large, but incomplete, material property data base exists for grade H-451. Work to obtain property data on HLM graphite has been relatively limited due to the less severe

service environment. All property data on H-451 and on HLM were documented by GA for the commercial HTGRs in the Graphite Design Data Manual [GDDM 1984]. These data will be used for the Conceptual Design (and perhaps Preliminary Design) of the NGNP core until replacement graphite is characterized. Alternatively, data for IG-110 graphite can be used if a decision is made to use this graphite for initial NGNP cores.³

To supply the FSV reactor with graphite for reload fuel, a stockpile of coke was produced to make H-451 graphite. This coke was derived from a selected, high-purity petroleum feedstock, specially processed to provide a material with near-isotropic properties. Since the remaining FSV coke supply is insufficient for continued graphite production, SGL Carbon, the producer of H-451 graphite, has taken the initiative to perform screening tests on cokes from several new feedstocks and on graphite processed from these cokes. The purpose of these tests is to select cokes which will produce graphite with properties and microstructural characteristics that most closely match those of H-451 graphite produced for FSV.

As part of the New Production Modular HTGR (NP-MHTGR) program, significant progress was made on the graphite technology program [Luci 1993a]. Under this program, GA⁴ prepared DDNs and Test Specifications, and ORNL prepared Test Plans and conducted the test programs. Test Plans were prepared in the following areas:

- Thermal Physical Properties of Graphites
- Fracture Mechanics Data for Graphite Core Components
- Fatigue Data for Graphite Core Components
- Irradiation of Graphite Materials in the ORNL High Flux Isotope Reactor
- Multiaxial Strength of Graphite Reactor Internal Components
- Graphite Mechanical Properties

ORNL completed much of the testing to determine unirradiated properties of H-451 graphite, but the testing programs for irradiated specimens were terminated early in 1993, following the decision to cancel the NP-MHTGR program. As part of this program, GA and ORNL developed a Graphite Material Specification for NP-MHTGR Fuel and Reflector Elements [Morrison 1993]. This Specification includes methods and procedures for sampling and for measuring graphite properties.

A Graphite and Ceramics Development Plan was also prepared for the commercial MHTGR [Luci 1993b], and includes cost and schedule estimates for completing the testing programs required to satisfy the DDNs.

³ The core designs using H-451 graphite, a replacement for H-451 graphite, or IG-110 graphite are not expected to be significantly different.

⁴ Under this program, GA and Combustion Engineering formed a partnership referred to as CEGA.

More recently, DOE National Laboratories have prepared a Materials Research and Development Program Plan [Hayner 2005] and a Graphite Technology Development Plan in support of the NGNP program [Windes 2007]. These plans build upon the experience obtained from previous technology development programs for gas-cooled reactors. The Graphite Technology Development Plan covers sampling requirements and test programs to obtain both unirradiated and irradiated data for physical, thermal, and mechanical properties. Costs, schedule, and an irradiation capsule test program are also described in this plan. Graphite samples for the first irradiation capsule were received at INL at the end of September.

General Atomics has prepared an NGNP Umbrella Technology Development Plan [Hanson 2007] that covers all areas of technology development, including graphite.

2 APPLICABLE DOCUMENTS

"Complete Design Data Manual " MANI 000274 Day A Company Atomics
"Graphite Design Data Manual," MAN 906374, Rev. A, General Atomics,
San Diego, CA, August 1984.
"NGNP Umbrella Technology Development Plan," PC-000543, Rev. 0,
General Atomics, San Diego, CA, July 2007.
"Next Generation Nuclear Plant Materials Research and Development
Program Plan," INL/EXT-05-00758, Rev. 2, Idaho National Laboratory,
Idaho Falls, ID, September 2005.
"Characteristics of First Loaded IG-110 Graphite in HTTR Core," JAEA-
Technology 2006-048, Japan Atomic Energy Agency, Tokai, Japan,
September 2006.
"Reactor Graphite Technical Development Status Report," CEGA-002817,
Rev. 1, General Atomics, San Diego, CA, October 1993.
"450 MW(t) MHTGR Reactor Graphite and Ceramics Development Plan,"
DOE-HTGR-90358, General Atomics, San Diego, CA, June 1993.
"Graphite Material Specification for NP-MHTGR Fuel and Reflector
Elements," CEGA-001803, Rev. 1, General Atomics, San Diego, CA, April
1993.
"Graphite Block Requirements for the GT-MHR Core," RDE 911116, Rev. 0,
General Atomics, San Diego, CA, February 2008.
"Graphite Technology Development Plan," PLN-2497, Rev. 0, Idaho
National Laboratory, Idaho Falls, ID, October 2007.

3 TEST PLAN FOR ADVANCEMENT FROM TRL 6 to TRL 7

This Test Plan is organized according to Design Data Need. The required data need to be obtained for the reactor service conditions during normal operation and accident conditions. These conditions are defined in the NGNP Umbrella Technology Development Plan [Hanson 2007] and include temperature, pressure, fast neutron fluence, and coolant impurity levels. For some tests, it may be impractical to obtain data under the specified NGNP conditions, and methodologies to extrapolate the data from test conditions to reactor conditions must be developed before the specific Test Specifications and Test Plans are approved.

3.1 Graphite Multiaxial Strength Data (DDN C.11.03.11)

3.1.1 Test Objective

The objectives of this test program are to verify the multiaxial strength data to reduce uncertainty in the design of the core graphite components and to confirm the probabilistic structural design criteria for replaceable graphite core elements.

3.1.2 Test Description

This experimental program will characterize the multiaxial strength properties of replaceable graphite core components for the NGNP. This effort will be primarily directed toward generating multiaxial strength data on unirradiated core graphites under ambient conditions. Multiaxial strength data will be generated on the new graphite selected to replace H-451 graphite and will include work on the effects of the following test parameters:

- Principal stress ratio
- Quadrant of the failure envelope

Billet sampling plans and specific experimental approaches have been developed to meet the design data needs. The data base will be sufficient to determine the failure surface in two-dimensional stress space to a reasonably attainable accuracy.

3.1.3 Test Conditions

The test will be performed at room temperature on unirradiated, unoxidized material.

3.1.4 Test Configuration/Set-Up

Thin-walled cylindrical specimens subjected to various combinations of axial tensile or compressive loading and internal or external pressure will be used. A total of 24 axial specimens will be obtained from each billet. Because of the radial strength variation within a billet, the side of the specimen closest to the outside of the billet will be marked to see if the

fracture locations correlate with the radial position in the billet. The center will be core-drilled from each specimen to provide material for companion specimens. In addition, the center of the billet will be available for testing. All of the billets will come from the same lot and the same class to minimize variability. The specimens for each stress ratio will be selected at random using a random number generator.

An ASTM Test Standard is under development for measuring multi-axial failure criteria [Windes 2007].

Thirteen different ratios of circumferential to axial stress ratios will be used including 0:1, 0:-1, 1:0, -1:0, 1:1.3, 1:2, 1:1, 1:2, 1:x, -1:1, -2:1 and -x:1. The 1:1.3 stress-ratio was selected based on the ratio of the tensile strengths of H-451 graphite in the radial and axial directions. The 1:-x and -x:1 tests will be similar in that the values of x will be determined based on the ratio of the circumferential tensile strength to the axial compressive strength, and the ratio of the circumferential compressive strength to the axial tensile strength, respectively. Twenty specimens will be tested for each of the stress ratios, except only ten specimens will be tested for each of the four stress ratios that require external pressure.

3.1.5 Test Duration

48 months, including completion of all test documentation

3.1.6 Proposed Test Location

Oak Ridge National Laboratory

3.1.7 Measured Parameters

Graphite multiaxial strength

3.1.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.1.9 Test Evaluation Criteria

The database must be adequate to determine the mean value failure surface and the associated variability as well as the specified minimum strength surface such that the survival probability is 99 % with a confidence level of 95 %.

3.1.10 Test Deliverables

<u>Deliverable</u> <u>Responsibility</u>

Test Specification Design Organization

Test Plan Technology Organization
Test Procedures Technology Organization
Test Status Reports Technology Organization
Test Report Technology Organization
Test Evaluation Report Design Organization

3.1.11 Cost, Schedule, and Risk

Cost (2008 \$K): 4,240

Schedule: Final data are needed 18 months before the end of final design

Risk

In the absence of obtaining statistical multiaxial strength data, the designer's alternative is to continue the use of maximum stress failure theory and/or its derivative, the modified Coulomb-Mohr theory, and estimate the errors and uncertainties on the basis of the uniaxial data and the biaxial data available for other graphites. Also, sufficient design margin must be provided to account for the uncertainties from which the reliabilities can be estimated, or cracking analysis must be performed to assess the failure modes and effects. This alternative may not be acceptable for safety evaluations, and it could also result in unnecessarily large structural cross sections and higher costs.

3.2 Graphite Fatigue Data (DDN C.11.03.12)

3.2.1 Test Objective

The objective of this test program is to obtain graphite fatigue strength data.

3.2.2 Test Description

This test program will be primarily directed towards generating fatigue data on unirradiated and irradiated core graphites at temperatures in the range from Room Temperature (RT) to 1600°C. This test program is closely integrated with other graphite test programs, particularly tensile strength and physical properties measurements.

A complete fatigue characterization will be performed, including tests under constant stress amplitude and variable stress amplitude conditions and will include the effects of the following test parameters:

Stress ratio (minimum to maximum stress), R=-1 to +1

- Stress amplitude, 65% to 90% of mean ultimate strength
- Spatial variation and orientation within billet
- Billet to billet variability
- Class to class variability
- Lot to lot variability
- Temperature, RT to 1600°C
- Oxidation
- Irradiation, fast neutron fluences up to 4×10^{25} n/m²

3.2.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007]

3.2.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards

3.2.5 Test Duration

36 months, including completion of all test documentation

3.2.6 Proposed Test Location

Oak Ridge National Laboratory

3.2.7 Measured Parameters

Fatigue tests will be performed in air at ambient temperature. High frequency (= 10 Hz) tests will be performed in sufficient numbers to satisfy the statistical requirements stated below. A number of additional tests will be performed to assess the effect of reactor operating environment on fatigue behavior.

3.2.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.2.9 Test Evaluation Criteria

The fatigue data generated in this testing program will establish the minimum fatigue strength under uniaxial cyclic loading conditions such that survival probability for a laboratory specimen is 99% with a confidence level of 95% for lifetimes ranging for 10² to 10⁵ cycles.

3.2.10 Test Deliverables

<u>Deliverable</u> <u>Responsibility</u>

Test Specification

Test Plan

Technology Organization

Test Procedures

Technology Organization

Test Status Reports

Technology Organization

Test Report

Technology Organization

Technology Organization

Test Evaluation Report Design Organization

3.2.11 Cost, Schedule, and Risk

Cost (2008 \$K): 1,000

Schedule: Final data are needed 18 months before the end of final design

Risk

In the absence of obtaining fatigue strength data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.3 Graphite Coke Source Qualification Data (DDN C.11.03.21)

3.3.1 Test Objective

The objective of this test program is to qualify new coke feedstocks for production of a graphite to replace H-451 graphite.

3.3.2 Test Description

To be determined by the selected graphite manufacturer.

3.3.3 Test Conditions

To be determined by the selected graphite manufacturer.

3.3.4 Test Configuration/Set-Up

To be determined by the selected graphite manufacturer.

3.3.5 Test Duration

To be determined by the selected graphite manufacturer. Estimated duration is 24 months, including completion of all test documentation.

3.3.6 Proposed Test Location

Graphite manufacturer facilities

3.3.7 Measured Parameters

Properties from new coke feedstocks to ensure acceptable graphite properties

3.3.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.3.9 Test Evaluation Criteria

To be determined by the selected graphite manufacturer

3.3.10 Test Deliverables

<u>Deliverable</u> <u>Responsibility</u>

Test Specification Design Organization

Test Plan Technology Organization
Test Procedures Technology Organization
Test Status Reports Technology Organization
Test Report Technology Organization
Test Evaluation Report Design Organization

3.3.11 Cost, Schedule, and Risk

Cost (2008 \$K): 2,000

Schedule: Final data are needed 18 months before the end of final design.

Risk

A replacement graphite for grade H-451 cannot be qualified for use in the NGNP without coke source qualification data.

3.4 Graphite Mechanical Properties Data (DDN C.11.03.13)

3.4.1 Test Objective

The objectives of this program are to determine the mechanical properties of the selected graphite materials for the replaceable reactor components and to determine the statistical variability of the mechanical properties. This data will be used to calculate probabilistic stress criteria to ensure compliance with plant availability goals and safety/reliability component requirements.

3.4.2 Test Description

Established methods will be used to determine graphite mechanical properties, including tensile, compressive, and flexural strengths, static and dynamic elastic modulus, poisson's ratio, and strain to failure.

The data shall include the effects of:

- Orientation and location that the sample is taken from the billet
- Variation from billet to billet
- Fast neutron fluence
- Temperature, ranging from shutdown conditions to the maximum service temperature
- Specimen size (volume)
- Irradiation creep
- Oxidation

3.4.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007].

3.4.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards, including those listed below:

Data Requirement	Test Method		
Stress strain	ASTM C749-02, Standard Test Method for Tensile Stress-		
relationships	Strain of Carbon and Graphite		
Flexural Strength	ASTM C1161-02c, Standard Test Method for Flexural		
	Strength of Advanced Ceramics at Ambient Temperature		
Tensile strength	ASTM C749-02, Standard Test Method for Tensile Stress-		
_	Strain of Carbon and Graphite		

Data Requirement	Test Method		
Compressive strength	ASTM C695-05, Standard Test Method for Compressive Strengths of Carbon and Graphite		
Static and Dynamic Elastic Modulus	ASTM C747-05, Standard Test Method for Elasticity and Fundamental Frequencies of Carbon and Graphite materials by Sonic Resonance		
Poisson's Ratio	ASTM C747-05, Standard Test Method for Elasticity and Fundamental Frequencies of Carbon and Graphite materials by Sonic Resonance		
Strain to failure	ASTM C565-93, Standard Test Method for Tension Testing of Carbon and Graphite Mechanical Materials		

3.4.5 Test Duration

36 months, including completion of all test documents

3.4.6 Proposed Test Location

Oak Ridge National Laboratory

3.4.7 Measured Parameters

Graphite mechanical properties, as indicated in Section 3.4.4

3.4.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.4.9 Test Evaluation Criteria

The data must be sufficient to determine the statistical distribution of the required properties so that the mean values and associated variabilities and the specified minimum strength (per ASME Subsection CE) can be established with 95% confidence.

3.4.10 Test Deliverables

<u>Deliverable</u>	<u>Responsibility</u>
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Test Status Reports	Technology Organization

Test Report Technology Organization
Test Evaluation Report Design Organization

3.4.11 Cost, Schedule, and Risk

Cost (2008 \$K): 4,000

Schedule: Final data are needed 24 months before the end of final design.

Risk

In the absence of obtaining graphite mechanical properties data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.5 Graphite Irradiation-Induced Dimensional Change Data (DDN C.11.03.14)

3.5.1 Test Objective

The objectives of this test program are to determine the irradiation induced dimensional change data for the selected graphite core and core support components and to determine the statistical variability of the data. These data will be used to calculate probabilistic stress criteria to ensure compliance with plant availability goals and graphite component safety/reliability requirements.

3.5.2 Test Description

This test program will generate data for characterizing the irradiation-induced dimensional change behavior of the graphite selected to replace grade H-451. This effort will be primarily directed towards generating dimensional change data for graphite irradiated in the temperature range 300°C to 1300°C. Data will be generated to account for the following parameters:

- Spatial variation and orientation within billet
- Billet-to-billet variability
- Class-to-class variability
- Lot-to-lot variability
- Temperature, 300° to 1600°C
- Neutron irradiation fluence, up to 4.5 x 10²⁵ n/m²
- Oxidation

3.5.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007]

3.5.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards. Data for dimensional and volume changes will be obtained.

3.5.5 Test Duration

36 months, including completion of all test documentation

3.5.6 Proposed Test Location

Oak Ridge National Laboratory

3.5.7 Measured Parameters

Irradiation-induced dimensional changes of graphite

3.5.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.5.9 Test Evaluation Criteria

The data must be sufficient to determine the irradiation induced dimensional change mean values and standard deviations to a reasonably attainable accuracy with 95% confidence.

3.5.10 Test Deliverables

<u>Deliverable</u> <u>Responsibility</u>

Test Specification Design Organization

Test Plan Technology Organization
Test Procedures Technology Organization
Test Status Reports Technology Organization

Test Evaluation Report Design Organization

3.5.11 Cost, Schedule, and Risk

Cost (2008 \$K): 1,100

Test Report

Schedule: Final data are needed 24 months before the end of final design.

Technology Organization

Risk

In the absence of obtaining graphite dimensional change data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.6 Graphite Irradiation-Induced Creep Data (DDN C.11.03.15)

3.6.1 Test Objective

The objectives of this test program are to determine the irradiation induced creep data for the selected graphite core and core support components and to determine the statistical variability of the data. These data will be used to calculate probabilistic stress criteria to ensure compliance with plant availability goals and graphite component safety/reliability requirements.

3.6.2 Test Description

This test program will generate data for characterizing the irradiation creep behavior of the graphite selected to replace grade H-451. This effort will be primarily directed towards generating irradiation creep data for graphite irradiated in the temperature range 550°C to 1300°C. Data will be generated to account for the following parameters:

- Isothermal conditions
- Cyclic non-isothermal conditions
- Creep with stress reversal
- Temperature, 550°C to 1300°C
- Neutron fluence, up to 4.5 x 10²⁵ n/m²

3.6.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007].

3.6.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards.

3.6.5 Test Duration

36 months, including completion of all test documentation

3.6.6 Proposed Test Location

Oak Ridge National Laboratory

3.6.7 Measured Parameters

Irradiation-induced creep data for graphite

3.6.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.6.9 Test Evaluation Criteria

The data must be sufficient to determine the irradiation induced dimensional change mean values and standard deviations to a reasonably attainable accuracy with 95% confidence.

3.6.10 Test Deliverables

Deliverable Responsibility

Test Specification Design Organization
Test Plan Technology Organization
Test Procedures Technology Organization

Test Status Reports
Test Report
Test Report
Test Report
Technology Organization

Test Evaluation Report Design Organization

3.6.11 Cost, Schedule, and Risk

Cost (2008 \$K): 3,300

Schedule: Final data are needed 24 months before the end of final design.

Risk

In the absence of obtaining graphite dimensional change data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.7 Graphite Thermal Properties Data (DDN C.11.03.16)

3.7.1 Test Objective

The objective of this test program is to obtain data for characterizing the thermal properties of the graphite selected to replace grade H-451 and reduce uncertainties in these data.

3.7.2 Test Description

This test program will generate data for characterizing the thermal properties of the graphite selected to replace grade H-451. This effort will be primarily directed toward generating thermal property data on unirradiated and irradiated graphite in the temperature range RT-1600°C. The thermal properties of specimens subjected to oxidation will also be determined.

Data for thermal conductivity, coefficient of thermal expansion, emissivity and specific heat will be generated and account for the following parameters:

- Spatial variation and orientation within billet
- Billet-to-billet variability
- Class-to-class variability
- Lot-to-lot variability
- Temperature, RT to 1600°C
- Oxidation
- Irradiation
- Thermal annealing

3.7.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007].

3.7.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards.

3.7.5 Test Duration

36 months, including completion of all test documentation

3.7.6 Proposed Test Location

Oak Ridge National Laboratory

3.7.7 Measured Parameters

Thermal conductivity, coefficient of thermal expansion, emissivity and specific heat

3.7.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for

Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.7.9 Test Evaluation Criteria

To be determined in part by sensitivity analyses performed for the reactor core design

3.7.10 Test Deliverables

<u>Deliverable</u> <u>Responsibility</u>

Test Specification
Test Plan
Technology Organization
Test Procedures
Test Status Reports
Test Report
Test Report
Test Specification
Technology Organization
Technology Organization
Technology Organization

Test Evaluation Report Design Organization

3.7.11 Cost, Schedule, and Risk

Cost (2008 \$K): 2,000

Schedule: Final data are needed 24 months before the end of final design.

Risk

In the absence of obtaining graphite thermal property data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.8 Graphite Fracture Mechanics Data (DDN C.11.03.17)

3.8.1 Test Objective

The objectives of this test program are to obtain data for critical stress intensity factors (K_{IC}) and strain energy release rates (G_{IC}) for crack initiation, stable crack growth, and crack arrest for the graphite selected to replace grade H-451, and to reduce uncertainties in these data.

3.8.2 Test Description

This test program will generate data for characterizing the fracture mechanics behavior of the graphite selected to replace grade H-451.

A complete fracture mechanics characterization of the graphite selected to replace grade H-451 will be performed, including a determination of stress intensity factors $(K_1,)$ and strain energy release rates (G_{1c}) for crack growth and crack arrest, and will account for the following parameters:

- Spatial variation and orientation within billets
- Billet to billet variability
- Class to class variability
- Lot to lot variability
- Oxidation
- Irradiation

3.8.3 Test Conditions

Room temperature in air

3.8.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards.

3.8.5 Test Duration

36 months, including completion of all test documentation

3.8.6 Proposed Test Location

Oak Ridge National Laboratory

3.8.7 Measured Parameters

Critical stress intensity factors (K_{IC}) and strain energy release rates (G_{IC}) for crack initiation, stable crack growth, and crack arrest.

3.8.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.8.9 Test Evaluation Criteria

The data base must be sufficient to establish the mean values of the above fracture mechanics properties to a reasonably attainable accuracy with 95% confidence.

3.8.10 Test Deliverables

Deliverable Responsibility

Test Specification Design Organization

Test Plan **Technology Organization Test Procedures Technology Organization** Test Status Reports **Technology Organization** Test Report **Technology Organization**

Test Evaluation Report **Design Organization**

3.8.11 Cost, Schedule, and Risk

Cost (2008 \$K): 1,300

Schedule: Final data are needed 24 months before the end of final design

Risk

In the absence of obtaining fracture mechanics data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.9 **Graphite Corrosion Data (DDN C.11.03.23)**

3.9.1 **Test Objective**

The objectives of this test program are to obtain data for the corrosion behavior caused by coolant impurities for the graphite selected to replace grade H-451, and to reduce uncertainties in these data.

3.9.2 **Test Description**

This test program will generate data for characterizing the corrosion behavior of the graphite selected to replace grade H-451. The data will account for the following parameters:

- Spatial variation and orientation within billets
- Billet-to-billet variability
- Class-to class variability
- Lot-to-lot variability
- Temperature
- Irradiation
- Primary coolant helium, varying H₂O, and H₂ concentrations
- Burnoff, >2%
- Tortuosity

The corrosion of core and core support component graphite by coolant impurities may be mass-transfer limited, chemical-reaction limited, or a combination of both; consequently, both processes must be characterized. The transport of coolant impurities is a combination of pore diffusion and permeation flow due to pressure gradients; the transport rates increase with increasing graphite burnoff. The former process is characterized by an effective diffusion coefficient; the reference correlation was obtained for H_2O transport in H-451 graphite with 1 % burnoff. The permeability and tortuosity of H-451 graphite have not been well characterized. The reference correlations for the kinetics of H-451 corrosion by coolant impurities are based primarily upon laboratory measurements on small unirradiated specimens in helium with high impurity levels at or near atmospheric pressure. Some data were obtained at elevated pressures (about 20 atmospheres) in the ORNL High Pressure Test Loop. Since the measurements were all made on unirradiated graphite, the effects of radiolysis and catalysis by fission metals on the graphite corrosion rate were not systematically investigated. The reaction of H_2O with H_2O with H_2O with H_2O with H_2O but not by H_2 but not by H_3 but not H_3 but not

3.9.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007].

3.9.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards.

3.9.5 Test Duration

36 months, including completion of all test documentation

3.9.6 Proposed Test Location

Oak Ridge National Laboratory

3.9.7 Measured Parameters

Correlations describing the corrosion of graphite by coolant impurities during normal operation and H_2O ingress events are needed under the conditions specified in the NGNP Umbrella Technology Development Plan [Hanson 2007]. Data are needed to characterize both the transport of coolant impurities and graphite corrosion products in graphite and the intrinsic kinetics for the reaction of water with graphite. To characterize the transport of coolant impurities in graphite, the porosity, tortuosity, and permeability of the graphite must be determined. To characterize the reaction kinetics, the reaction rate must be determined as a function of temperature, impurity concentrations, system pressure, and time. In addition, the effects of radiolysis and catalysis by graphite impurities and by fission metals on the reaction

kinetics must be determined. Finally, the effects of partial graphite burnoff on both the mass transfer processes and the intrinsic reaction kinetics must be quantified.

3.9.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.9.9 Test Evaluation Criteria

Sufficient data are needed to predict the burnoff rate and profile within a factor of 2 with 95% confidence.

3.9.10 Test Deliverables

<u>Deliverable</u> <u>Responsibility</u>

Test Specification Design Organization

Test Plan Technology Organization
Test Procedures Technology Organization
Test Status Reports Technology Organization
Test Report Technology Organization

Test Evaluation Report Design Organization

3.9.11 Cost, Schedule, and Risk

Cost (2008 \$K): 2,200

Schedule: Final data are needed 24 months before the end of final design.

Risk

In the absence of obtaining graphite corrosion data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.10 Graphite Corrosion Data for Methods Validation (DDN C.11.03.19)

3.10.1 Test Objective

The objectives of this test program are to obtain integral graphite corrosion data for the purpose of validating computer codes and models that predict corrosion behavior in the graphite core.

3.10.2 Test Description

A characterization of the steam oxidation behavior of the graphite selected to replace grade H-451 will be performed under simulated reactor environment conditions, and will account for the following parameters:

- Temperature
- Primary coolant chemistry
- Pressure
- Burnoff
- Sample size
- Inlet gas flow rate
- Inlet gas temperature

3.10.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007].

3.10.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards.

3.10.5 Test Duration

36 months, including completion of all test documentation

3.10.6 Proposed Test Location

Oak Ridge National Laboratory

3.10.7 Measured Parameters

Graphite-steam oxidation data for validation of the integrated models and computer codes used to predict graphite corrosion in the NGNP core under normal operation and during high moisture ingress events are needed, under the conditions specified in the NGNP Umbrella Technology Development Plan [Hanson 2007]. Particular attention must be given to transport of coolant impurities in fuel element graphite and to the effect of catalysis by graphite impurities and fission metals. The data base used for code validation must be independent from the data from which the individual correlations in the overall design method (effective diffusivities, reaction kinetics, etc.) were originally derived, in accordance with QA requirements and project procedures for computer code validation.

3.10.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.10.9 Test Evaluation Criteria

Sufficient data must be obtained such that in the predictive methods are accurate to within a factor of 3 at 95% confidence.

3.10.10 Test Deliverables

<u>Deliverable</u> <u>Responsibility</u>

Test Specification Design Organization

Test Plan Technology Organization
Test Procedures Technology Organization

Pre-Test Prediction Report Design Organization

Test Status Reports Technology Organization
Test Report Technology Organization
Test Evaluation Report Design Organization

3.10.11 Cost, Schedule, and Risk

Cost (2008 \$K): 1,200

Schedule: Final data are needed 24 months before the end of final design.

Risk

In the absence of obtaining graphite corrosion data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.11 Graphite Oxidation Data for Postulated Accidents (DDN C.11.03.18)

3.11.1 Test Objective

The objectives of this test program are to obtain data for the oxidation behavior during low-frequency air-ingress events for the graphite selected to replace grade H-451, and to reduce uncertainties in these data.

3.11.2 Test Description

This test program will generate data for characterizing the oxidation behavior of the graphite selected to replace grade H-451.

In several previous experiments, high airflow rates, electrical heaters, and preheated air were used, which precluded convective heat removal and supplied oxygen to the entire channel length. As expected, rapid temperature increases and oxidation rates were eventually obtained in these experiments. However, these conditions should not exist during NGNP conduction cooldown scenarios and the transient behavior is expected to be substantially less severe. Key parameters that affect temperatures and oxidation rates include the type of graphite, initial graphite temperature, inlet air temperature, air flow rate and oxygen content, channel length to diameter ratio, and the ratio of coolant surface area to graphite volume. For the NGNP, the graphite temperatures may be significantly higher than the values used in previous experiments. At sufficiently high temperatures, the effective reaction rate will be limited by the mass-transfer rate of oxygen from the gas flow to the graphite and will be only weakly dependent on temperature. Previous predictions indicate that the gas flow is buoyancy-driven and the massflow rates are relatively low. Essentially all of the oxygen is depleted from the gas flow well before exiting the core, and nearly all of the oxidation occurs in the lower reflector, lower portions of the active core, and core support structure. The predicted oxidation rates are relatively low and nearly constant with time. The predicted temperatures do not rapidly escalate with time and the predicted behavior is not indicative of "runaway" oxidation. This behavior needs to be confirmed for NGNP accident conditions.

3.11.3 Test Conditions

As specified in the NGNP Umbrella Technology Development Plan [Hanson 2007].

3.11.4 Test Configuration/Set-Up

To be determined by the Technology Organization, consistent with applicable ASTM standards.

3.11.5 Test Duration

36 months, including completion of all test documentation

3.11.6 Proposed Test Location

Oak Ridge National Laboratory

3.11.7 Measured Parameters

Analyses of air ingress during NGNP accident conditions should include the feedback of chemical heat-generation rates on temperatures with sufficient spatial resolution to determine

local effects. Also, the effects of potential carbon monoxide combustion and the resulting high gas temperatures should be assessed. Data is needed for air-graphite intrinsic reaction rates for accident conditions. Data is needed for oxygen diffusion rates in graphite. Data is needed for air-graphite reaction effects on graphite mechanical strength properties as a function of burnoff. Data for gas temperatures and composition are needed to confirm graphite mass-loss rates, CO combustion models, and to assess the potential for flammable gas buildup.

3.11.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.11.9 Test Evaluation Criteria

To estimate fuel failure and fission-product release, local temperatures and local oxidation rates must be predicted to within a factor of 3 at 95% confidence.

3.11.10 Test Deliverables

Deliverable Responsibility

Test Specification Design Organization

Test Plan Technology Organization
Test Procedures Technology Organization

Pre-Test Prediction Report Design Organization

Test Status Reports Technology Organization
Test Report Technology Organization
Test Evaluation Report Design Organization

3.11.11 Cost, Schedule, and Risk

Cost (2008 \$K): 1,900

Schedule: Final data are needed 24 months before the end of final design.

Risk

In the absence of obtaining graphite oxidation data, the designer's alternative is to continue to use existing data and include additional design margin to cover uncertainties. This alternative may not be acceptable for safety evaluations.

3.12 Graphite Destructive and Non-Destructive Examination Data (DDN C.11.03.20)

3.12.1 Test Objective

The objectives of the NDE test program are to develop NDE techniques for detection of unacceptable flaws in production graphite and to determine graphite strength for component classification. Data will be produced to assess the accuracy and limitations for the graphite selected to replace grade H-451. The selected approach is to use nondestructive examination in combination with a minimum of destructive testing to ensure that production graphite satisfies specifications.

3.12.2 Test Description

Nondestructive techniques, including eddy current tests and sonic velocity/attenuation measurements, will be developed to detect flaws, correlate sonic velocity with elastic modulus, and correlate sonic attenuation with tensile strength. Other NDE techniques may be developed at the discretion of the Technology and manufacturing organizations.

3.12.3 Test Conditions

Room temperature in air

3.12.4 Test Configuration/Set-Up

To be determined by the Technology and Manufacturing Organizations, consistent with applicable ASTM standards.

3.12.5 Test Duration

24 months, including completion of all test documentation

3.12.6 Proposed Test Location

Oak Ridge National Laboratory or graphite manufacturer

3.12.7 Measured Parameters

Eddy current tests for flaw detection will be performed on samples machined from full-size billets, on full-size billets, and on machined fuel elements. Tests will be applied toward the detection of surface and subsurface flaws in full-size billets and in the web region of machined elements using both differential and absolute probe techniques.

Sonic velocity and attenuation measurements will be performed in conjunction with tensile tests to develop correlations for sonic velocity versus elastic modulus, and sonic attenuation versus

mean tensile strength. Data will be obtained as a function of position and orientation within billet and between billets in order to assess the accuracy of the method.

3.12.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.12.9 Test Evaluation Criteria

To be determined by the Technology and Manufacturing Organizations

3.12.10 Test Deliverables

<u>Deliverable</u> Responsibility

Test Specification Design Organization

Test Plan Technology Organization
Test Procedures Technology Organization

Pre-Test Prediction Report Design Organization

Test Status Reports
Technology Organization
Test Report
Technology Organization
Test Evaluation Report
Design Organization

3.12.11 Cost, Schedule, and Risk

Cost (2008 \$K): 2,000

Schedule: Final data are needed 24 months before the end of final design.

<u>Risk</u>

In the absence of obtaining NDE data, the designer's alternative is to use destructive techniques, which will increase costs and design margins because of higher uncertainties.

4 TEST PLAN FOR ADVANCEMENT FROM TRL 7 to TRL 8

Advancement to TRL 8 is achieved after instrumented tests are performed as part of NGNP startup testing to confirm physical, mechanical, and thermal properties. Inspections of selected fuel and reflector elements will be performed at the end of startup testing.

This plan will be developed in more detail during the preliminary and final design phases.

5 SCHEDULE

The schedule for this test program is closely tied to the schedule for the capsule irradiation program described in [Windes 2007]. Testing on irradiated samples must be completed approximately 18 months before NGNP startup testing begins. The durations for individual tests given in the previous sections are estimates for the approximate total time required to complete that portion of the test program and do not necessarily represent continuous time periods. During the Conceptual Design Phase, the Design and Technology Organizations will work together to prioritize the individual tests that make up the test program.

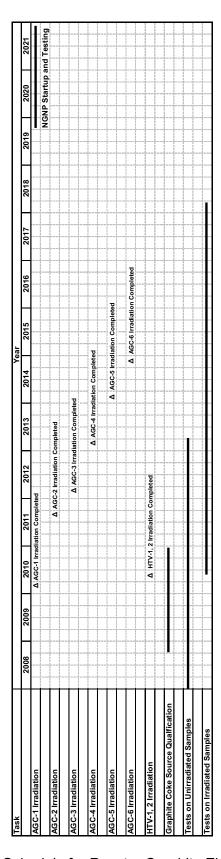


Figure 5-1. Overall Schedule for Reactor Graphite Elements Test Program

